# SQM stars around pulsar PSR B1257+12

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**Abstract:** Following Wolszczan's landmark discovery of planets in orbit around pulsar PSR B1257+12 in 1991, over 300 planets in more than 200 planetary systems have been found. Therefore, the meaning of Wolszczan's discovery cannot be overestimated. In this paper we aim to convince the reader that the objects accompanying pulsar PSR B1257+12 are more exotic than thought so far. They might not be ordinary planets but dwarf strange quark stars, whereas the pulsar might be a quark star with standard mass, not a neutron star. If this was the case, it would indicate that strange quark matter is the ground state of matter.

## I. INTRODUCTION

The millisecond pulsar PSR B1257+12 with the estimated age of 800 millions years, is located at a distance of 300 parsecs from the Earth. The tiny pulsar is being orbited by three bodies with masses 0.025, 3.9, and 4.3 of the Earth mass, typical of ordinary planets, and the respective radii of 0.19, 0.36 and 0.46 *AU* [1], [2]. For that reason, the bodies are considered to be planets. It was clear from the start, that the planetary system around PSR B1257+12 was unusual. Before Wolszczan's discovery, the existence of planets around neutron stars had not been considered seriously. If the planets were to be remnants of a planetary system existing around the progenitor star of PSR B1257+12, then it would be highly improbable for these planets to have survived the supernova explosion accompanying the neutron star's birth, since then compact bodies acquire velocities high enough to escape from the binding potential of the gravitational well of the surrounding matter. These planets might also had been formed already after the supernova explosion and the neutron star's formation. In particular, models of planetary system formation around pulsar accreting matter from its companion have been suggested [3]. However, this scenario seems also improbable because of strong radiation in the pulsar's vicinity [4]. Therefore, another hypothesis seems worth considering. The objects in orbit around PSR B1257+12 may be just miniature quark stars.

## II. STRANGE QUARK MATTER AS A BUILDING MATERIAL OF MINI-STARS

A quark star is a hypothetical object consisting of strange quark matter (SQM). SQM is a mixture of quasi-free quarks $u$, $d$, $s$ and electrons, all of which form relativistic fermi gas. If SQM is the ground state of strong interactions, then one could expect strange stars to form in space. For SQM to be the ground state, one needs the minimum of energy per baryon to be not greater than the energy per baryon for the strongest bound nucleus in nature – the nucleus of iron-56. Hence, $(\rho_E/n_B)_{SQM} \leq E(\mathrm{Fe}^{56})/56 = 930.4\mathrm{MeV}$ at zero pressure, where $\rho_E$ is the energy density and $n_B$ the baryon density. The possibility of existence of such objects was put forward first in [5]. The easiest way to obtain a phenomenological equation of state for SQM, is to consider the following simplified model [6]. Suppose that quarks form ultra-relativistic and electrically neutral quantum gas of non-interacting fermions in the $\beta$-equilibrium at temperature $T = 0[K]$. In this case, the pressure $p$ and the total energy density $\rho_E$ are

$$p = \frac{3}{4}\left(\rho_E - 4B\right), \qquad \rho_E = \frac{9\pi^{2/3}}{4}\hbar c n_B^{4/3} + B,$$

where $n_B$ is the baryon density and $B$ is the bag constant, $B = 50 \div 200\,[\mathrm{MeV/fm}^3]$. These equations are valid when the Fermi energy is much higher than the rest energy of the heaviest quark (in our numerical calculations we included also the strange quark mass, but the full form of the resulting equations is not important here).

The maximal mass and the corresponding size of a quark star are close to those for a neutron star. With the assumed example values $B = 70\,[\mathrm{MeV/fm}^3]$ and the strange quark mass $m_s = 150\,[\mathrm{MeV}/c^2]$, SQM would be the ground state for strong interactions. Then, the maximal mass of a quark star made of SQM would be $\approx 1.68\,M_\odot$ with the corresponding areal radius of about 9.3 [km][**?** ], whereas a neutron star with the UV14+TNI equation of state [7] attains $M_{\max} = 1.83\,M_\odot$ at $R = 9.5$ [km], see figure 1. Here, the similarities end. Only for sufficiently massive neutron stars, their gravitational field could prevent neutron matter from disintegration. Thus, there is the lower bound for masses of neutron stars. For realistic equations of state the minimum is approximately $0.1M_\odot$ [8]. Unlike for neutron stars, there would be no such a limit for SQM stars bound mainly by quark forces. Consequently, there are possible SQM stars of arbitrary low mass and radius. The mass-radius diagram for SQM stars is also different, see figure 1(b).
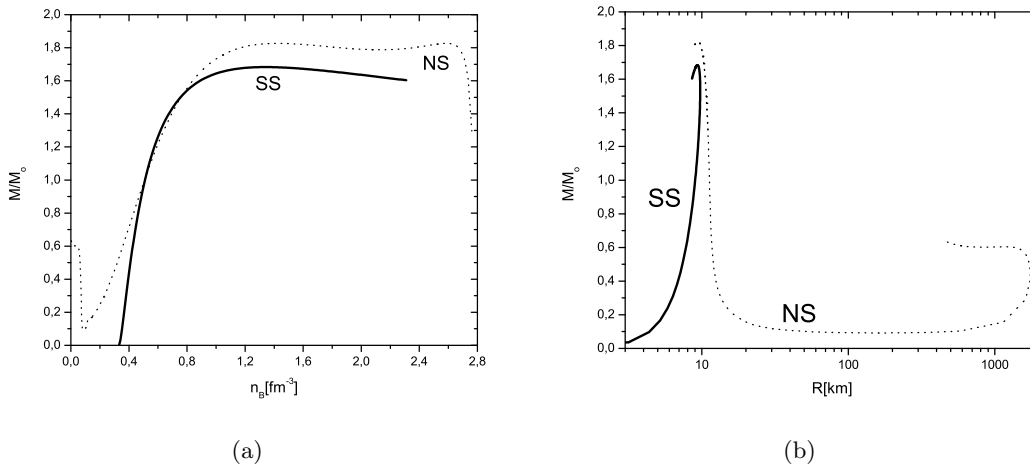
(a)



(b)

FIG. 1: Masses of quark stars as a function of central baryon density compared with a similar relation for a neutron star with a crust shell (a), and the *mass-areal radius* relation for SQM stars and similar relation for a neutron star with crust shell (b). Both cases assume bag constant $B = 70[\text{MeV}/fm^3]$, the strange quark's mass $150[\text{MeV}/c^2]$, and the UV14+TNI equation of state for the neutron star.

Low mass quark stars have small radii, while the radii of neutron stars grow with decreasing mass.

Confirmation of the presence of quark stars in space would indicate that SQM is the ground state for strong interactions. It is thus natural that astrophysicists have been intensively searching for such objects [9],[10]. Unfortunately, this endeavor is difficult, since quark and neutron stars are hardly distinguishable from each other in the range of masses close to $1.4\,M_\odot$, typical of pulsars, in which range the mass-radius relations are similar for both kinds of stars. On the other hand, it may turn out that quark stars have been already found.

### III.   SQM AND WOLSZCZAN'S SYSTEM AROUND PSR B1257+12

The pulsar PSR B1257+12 is being orbited by three bodies of masses 0.025, 3.9 and 4.3 in units of Earth mass. Owing to small masses, the objects are regarded as planets. The possibility the planets might be miniature compact stars has been already suggested in [11] in the context of pulsar PSR B1828-11 precession torqued by a quark planet. Masses of these objects are too small for them to be neutron stars. If they were to be compact objects, their building material would have to be made of SQM. If this really was the case, it would mean that PSR B1257+12 must be a quark star and SQM is the ground state for strong interactions.

Suppose that the objects orbiting PSR B1257+12 are SQM stars and assume that $B = 70\,[\text{MeV}/\text{fm}^3]$ and $m_s = 150\,[\text{MeV}/c^2]$. Since for such small stars the energy density must tend to the energy density on their surface $\rho_{ext}$, and since $2GM(r)/(rc^2) \ll 1$, the relation between the total mass $M$ and the physical radius $R$ of a low mass SQM star is nothing but $M = \frac{4\pi}{3}\rho_{ext}R^3$
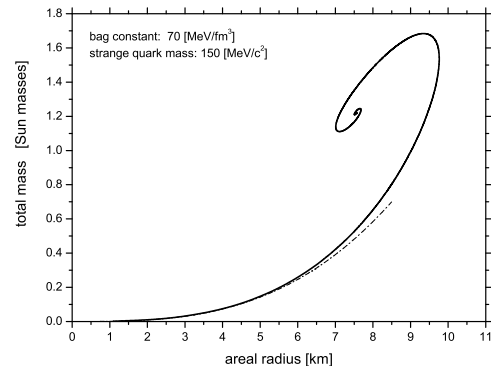


FIG. 2: Comparison of Newtonian $M - R$ relation (*dash-dot line*) and General-Relativistic $M - R$ relation (*solid line*) for a strange quark star. The assumed strange quark mass is $150\,[\text{MeV}]$ and the bag constant is $70\,[\text{MeV} \cdot \text{fm}^{-3}]$.

which, for the assumed parameters, gives the following mass-radius relation in Newtonian limit $MR^{-3} \approx 1.1413 \times 10^{-3}[\text{M}_\odot/\text{km}^3][\textbf{?}\;\;]$ (comparison between this relation and that obtained in the framework of General Relativity is illustrated in figure 2). Therefore, the stars' radii are of about 40, 217, and 225 meters, respectively. The central pulsar of mass $1.4M_\odot$ has the areal radius of about 9.75 [km]. Figure 3 shows energy density and pressure as functions of the areal radius for two example SQM stars.

What could have caused the mini-quark stars to find themselves in the pulsar vicinity? The first possibility is detachment of quark matter from the central pulsar during its formation phase, when the "boiling" strange matter core could eject some fragments, so that they start
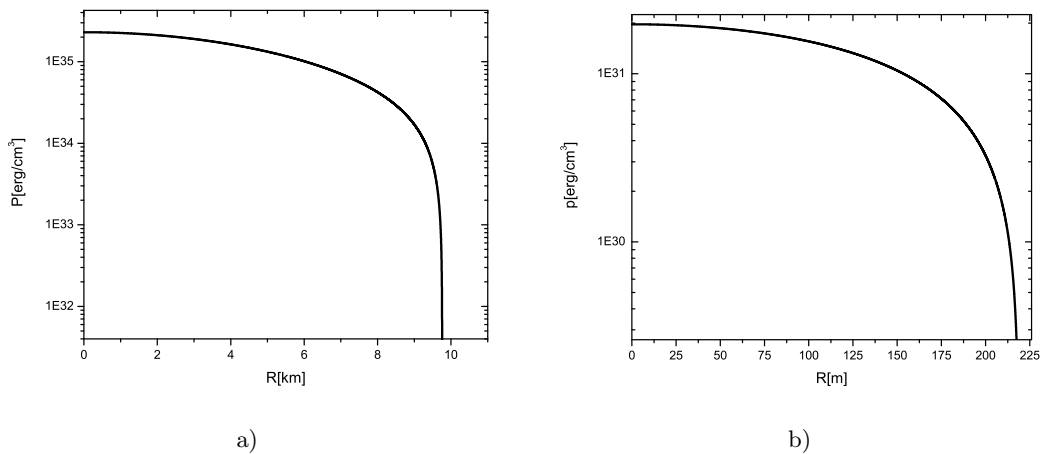
a)                                                          b)

**FIG. 3:** Cross section through a quark star of mass $1.4 M_\odot$ (a) and $3.9 M_\oplus$ (b). The assumed values for the bag constant is $B = 70 \text{MeV/fm}^3$, and the strange quark mass $m_s = 150 \text{MeV}/c^2$).

to orbit around the strange star. However, this mechanism does not explain why the orbits of the three planets are nearly circular and almost coplanar (at least, for two of them) [14]. These features make the planetary disk origin of the pulsar planets very likely. The planetary disk stability and the planet formation present a lot of unknowns and require ad hoc assumptions [15].

Here we propose another scenario. The present rotation period of pulsar B1257+12 is of about $P = 6.2$ ms and it decelerates with the rate $\dot{P} = 1.14 \times 10^{-19}$ [12]. The pulsar has the feature of a pulsar spun up in a binary system – it is a millisecond pulsar and, at the same time, it has comparably small deceleration rate and weak magnetic field. It seems therefore probable the pulsar might have had a companion from which it had been accreting matter. In this case it is difficult to estimate the age and the initial rotation velocity of a compact object. However, during the accretion phase, the compact object, by assumption being a quark star, could have spun up to

the velocities necessary to detach matter from its surface in the equatorial region. If only the accretion were sufficient to accelerate the star to the Keplerian frequency, which is about 1 KHz for strange star [13], then several bubbles of quark matter could start to orbit the central star. In a natural way their trajectories would be circular and coplanar. Being pieces of strange matter they would be completely resistant to the unfriendly pulsar environment heated by pulsar wind or accretion which may evaporate the normal planet.

## IV.  SUMMARY

In this paper we put forward the hypothesis that the planets orbiting the pulsar PSR B1257+12 may be quark stars made of strange quark matter. This is alternative to the currently accepted hypothesis that the system is composed of "ordinary" planets.

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